

The Potential of Photovoltaics



AIMCAL 2008

2008 Fall Conference
Vacuum Web Coating

Brent P. Nelson

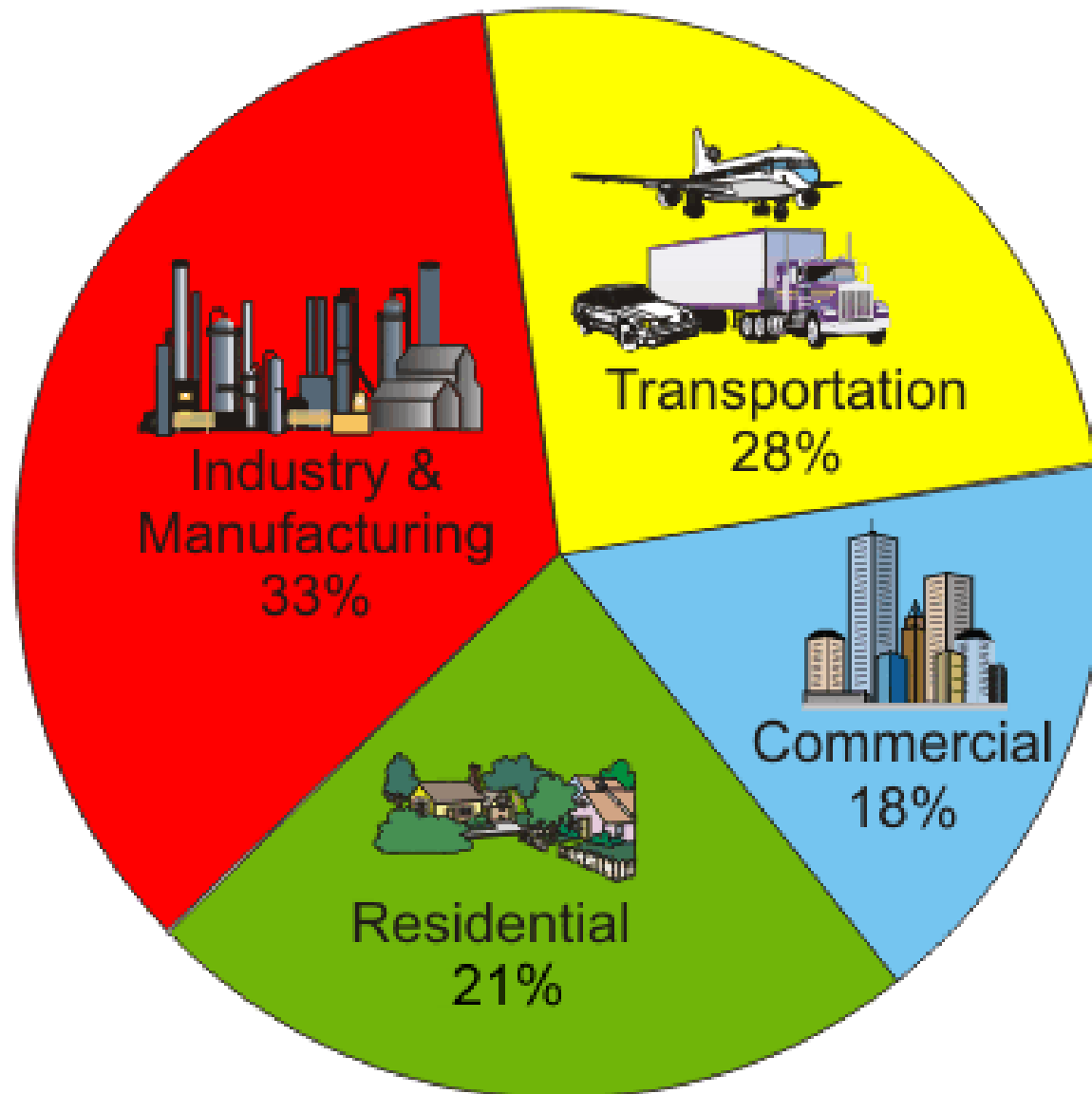
October 22, 2008



The Potential of PV: Course Outline

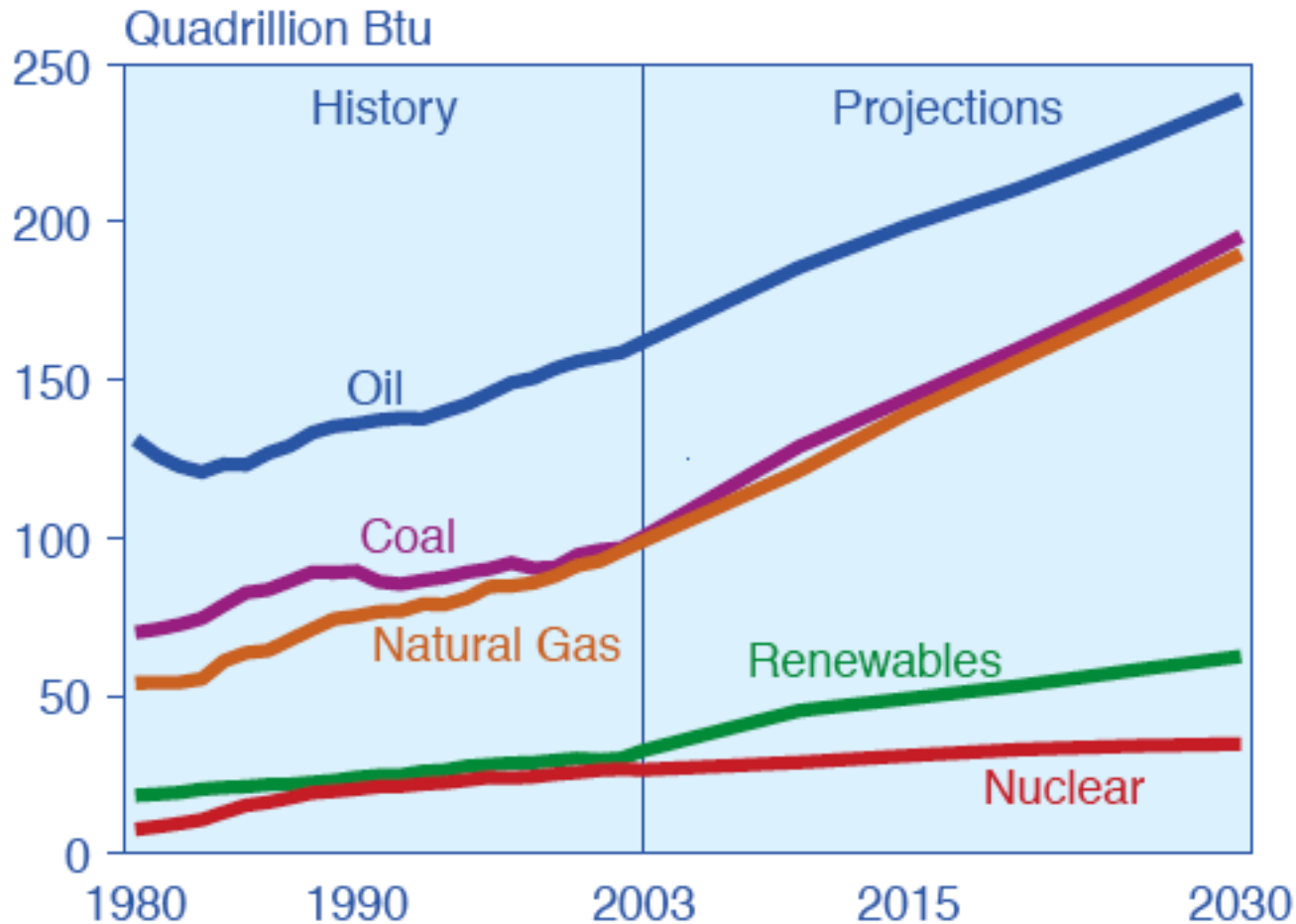
1. The Energy Market
2. Introduction to Photovoltaics (PV)
3. Current PV Technologies
 - a) crystalline silicon (c-Si)
 - b) amorphous silicon (a-Si:H)
 - c) cadmium telluride (CdTe)
 - d) copper indium gallium selenide (CIGS)
 - e) others, concentrator PV, organic PV, sensitized cells, etc.
4. Technology Comparison
5. PV Technology Trajectory

Breakdown of US Energy Use

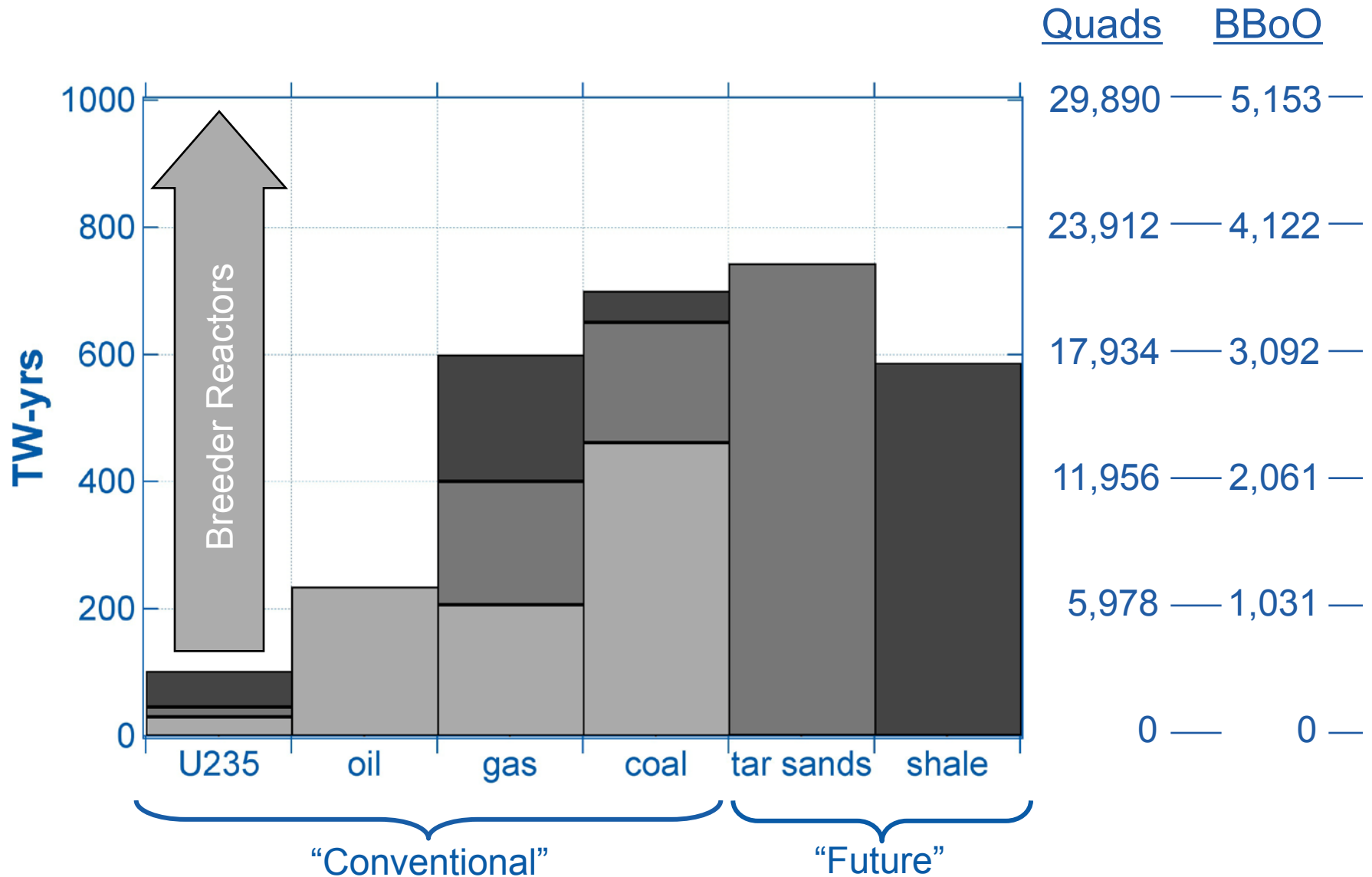


We use Mostly Chemical Energy

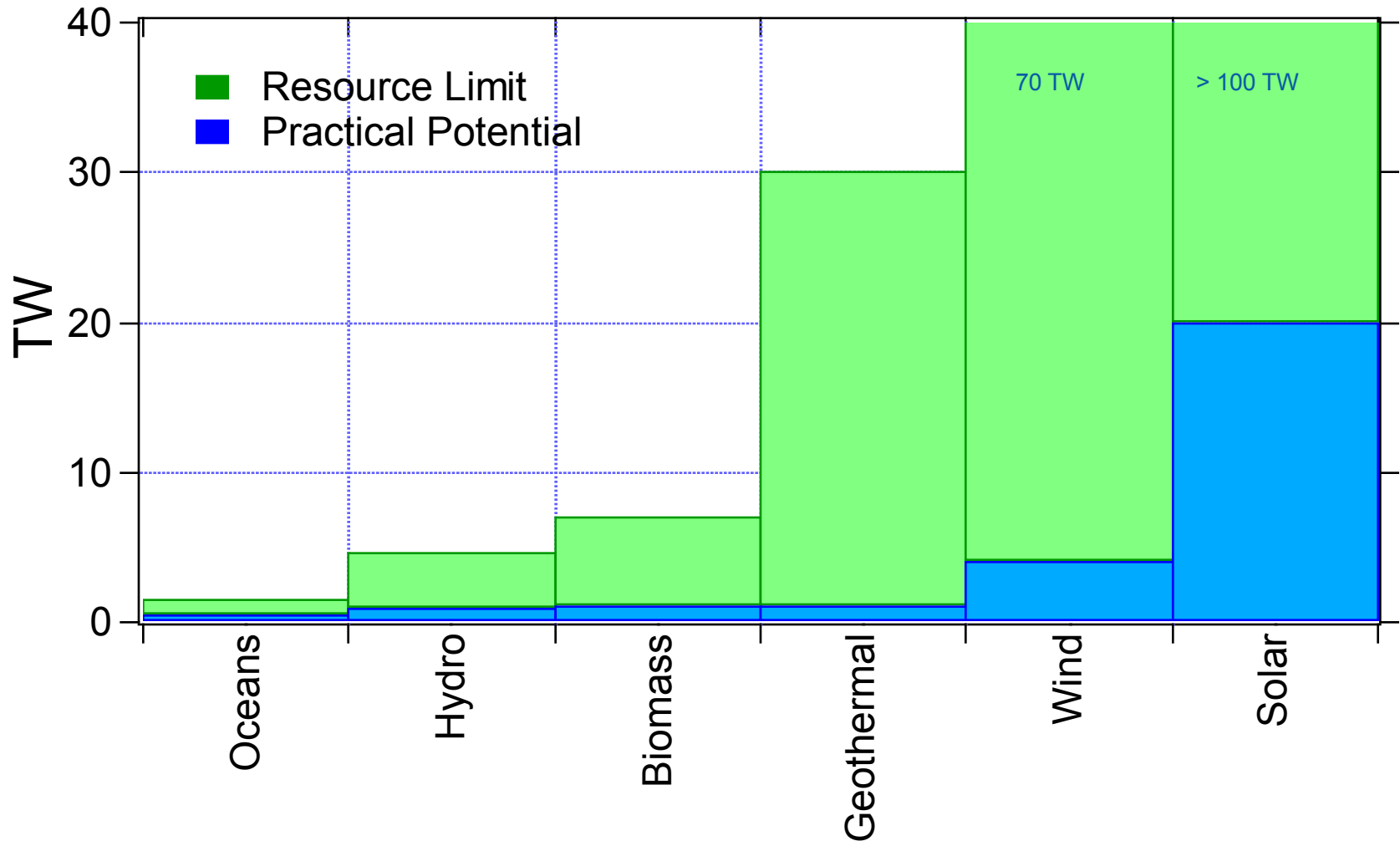
Figure 3. World Marketed Energy Use by Energy Type, 1980-2030



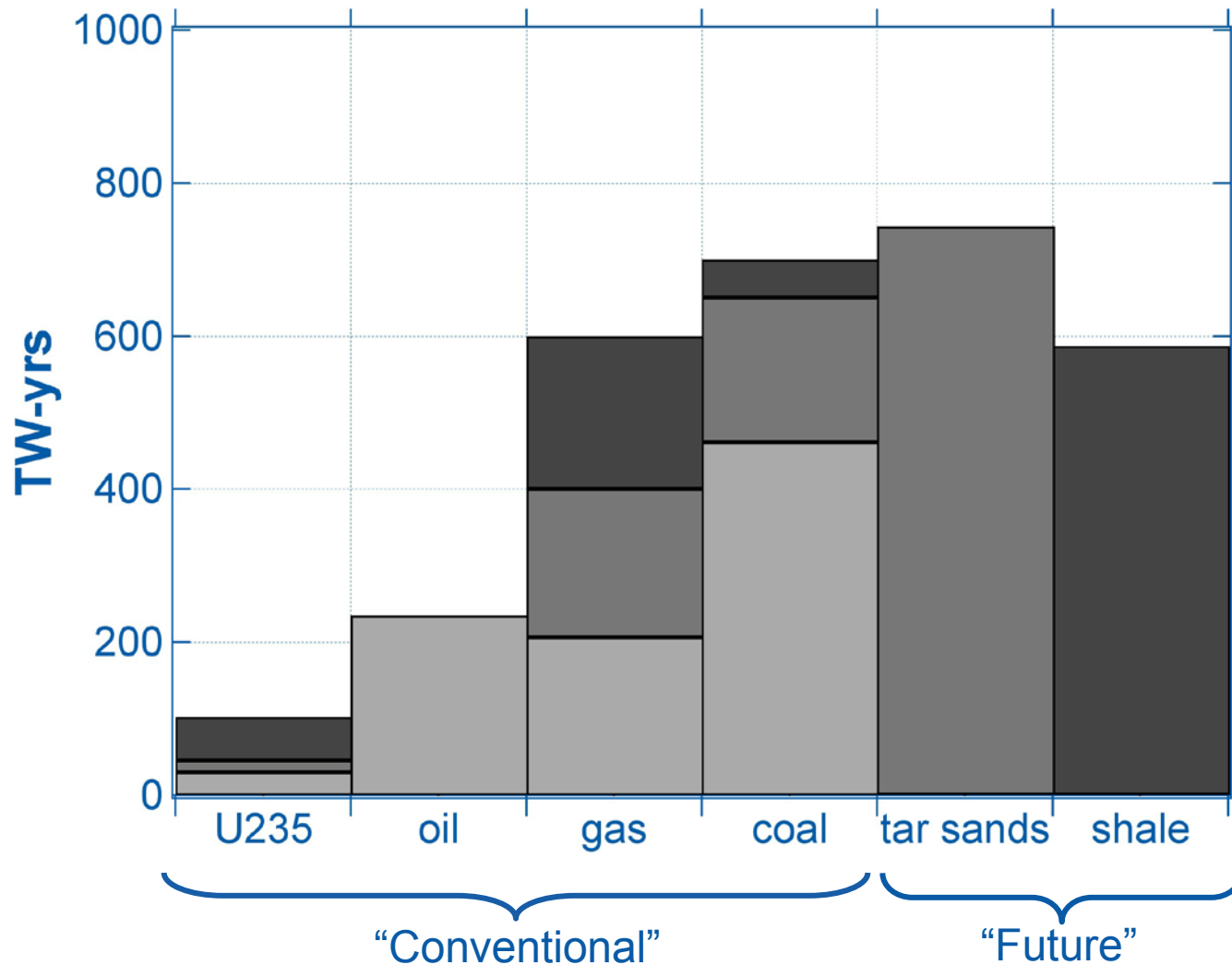
World's Consumable Resources



Sustainable Resource Potential



Consumable Resources



Hours ←

80

64

48

32

16

0

What are these units of time
of sunlight hitting the earth?



Solar Energy Technologies

Concentrating
Solar Power



Passive Solar
(space heating)



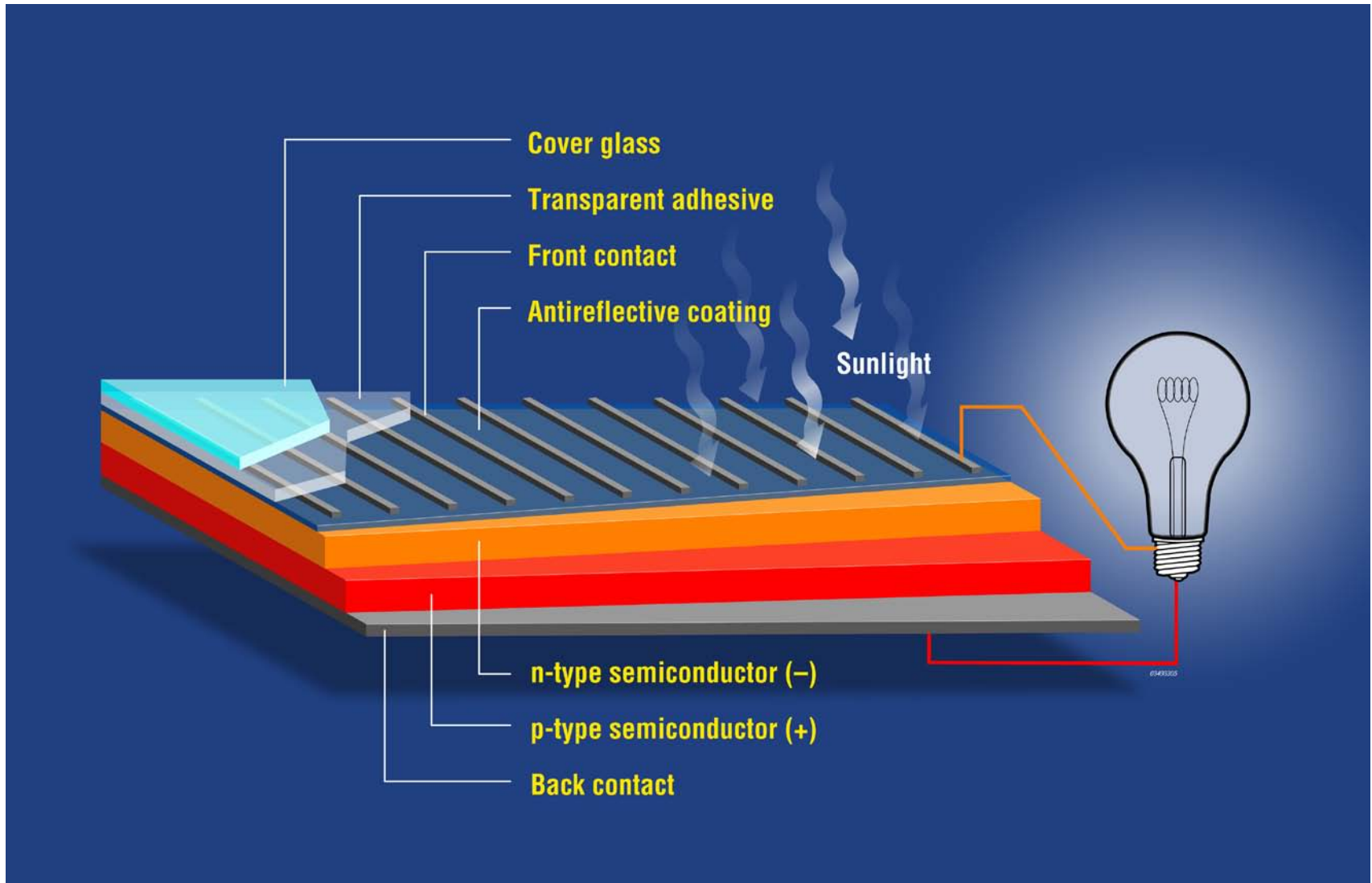
Solar
Hot Water



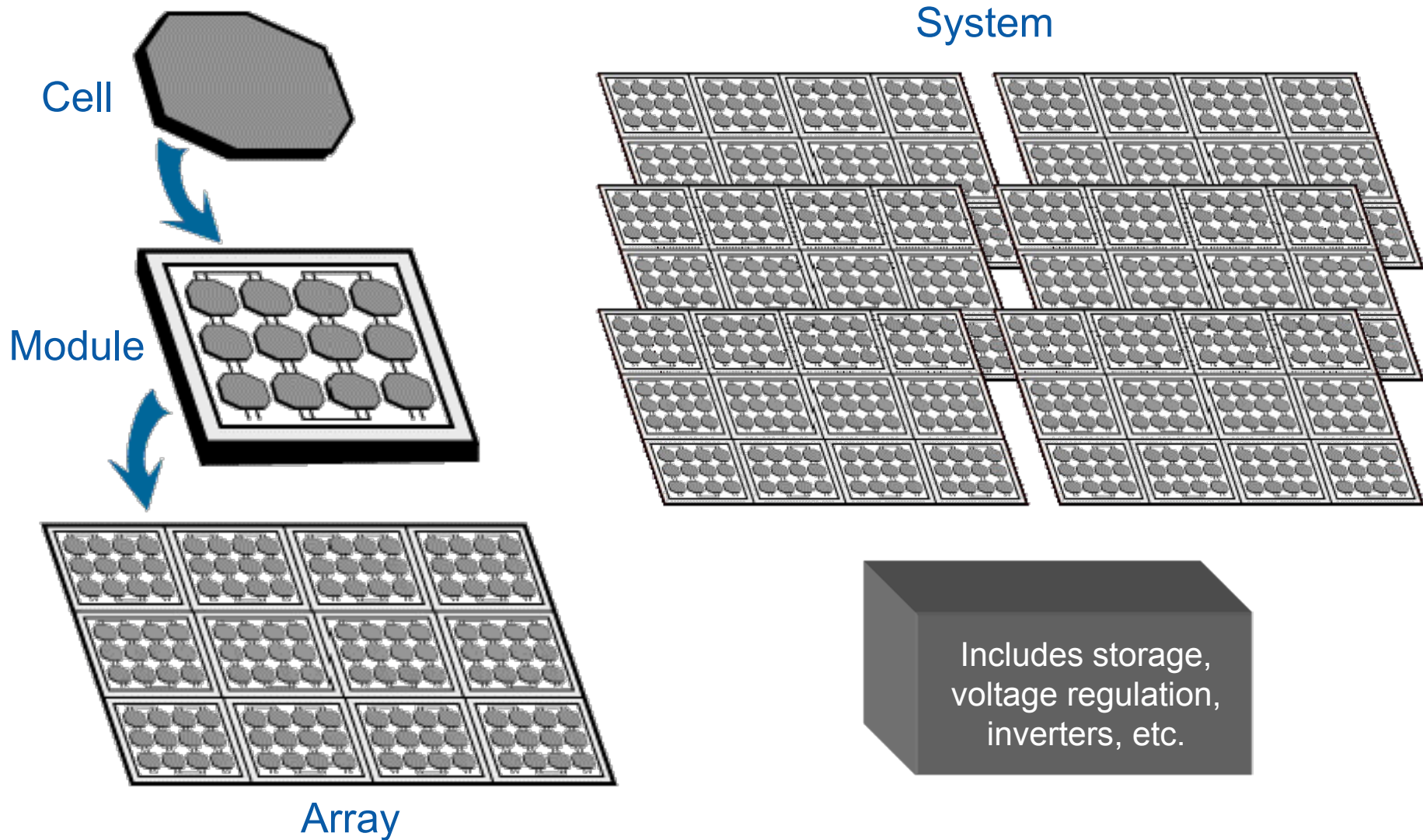
Solar Electric - Photovoltaics



The Basic Solar Cell

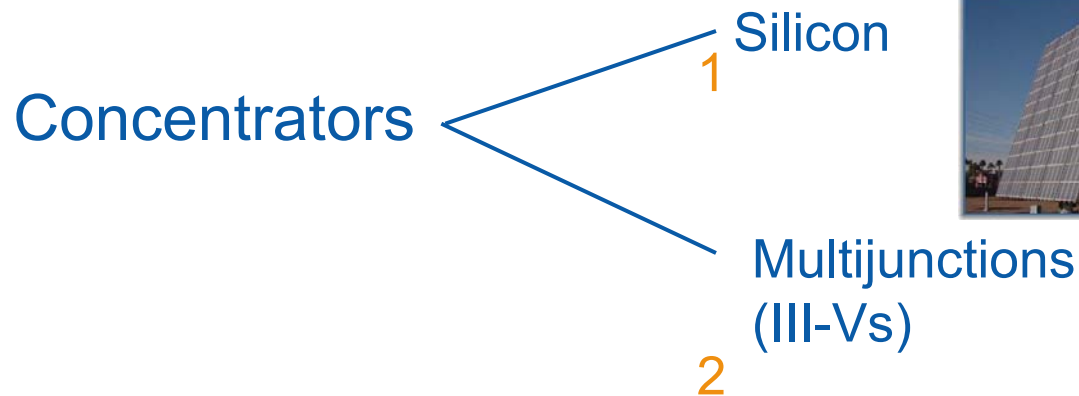
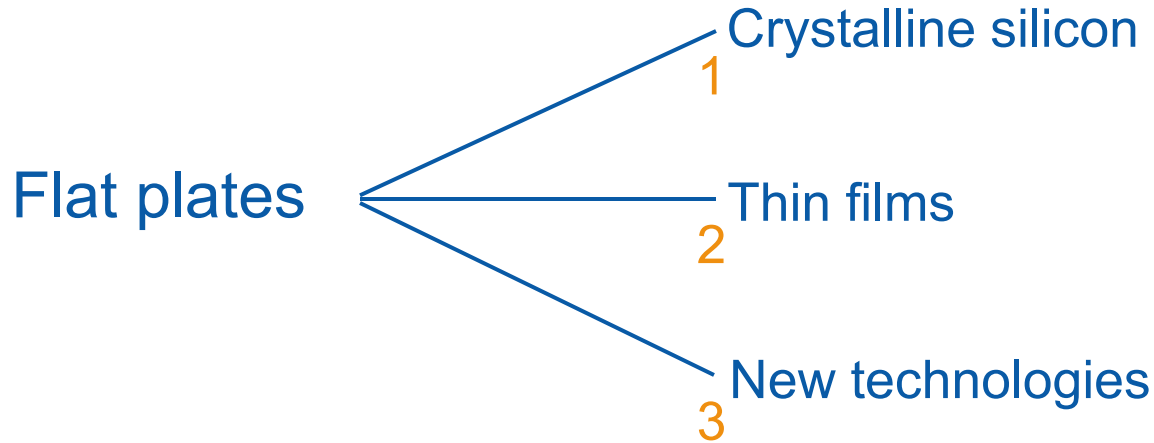


PV Systems Building Blocks



PV Technologies

Generation

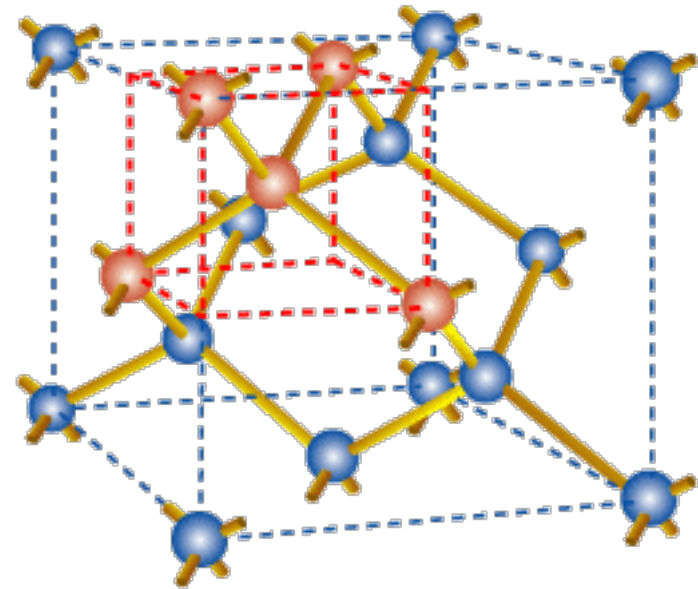
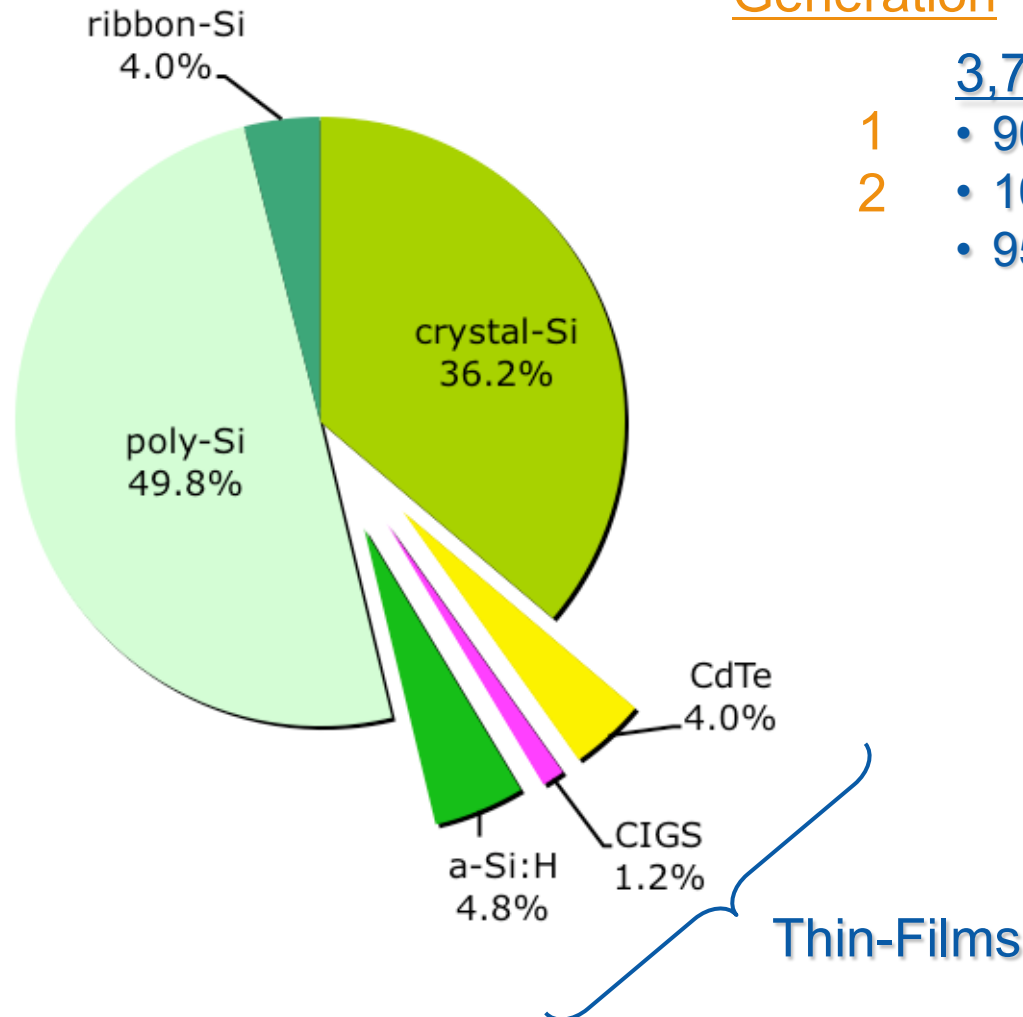


2007 Flat Plate Module Production

Generation

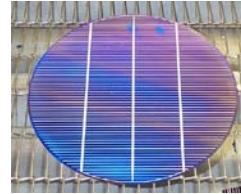
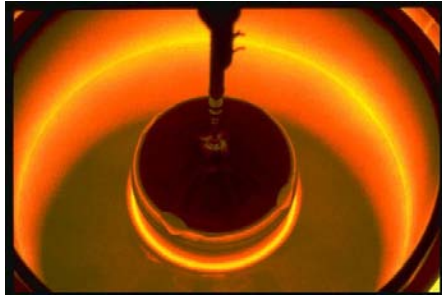
3,733 MW Total Production

- 1 • 90% is crystalline silicon
- 2 • 10% is thin-films (pulled out)
 - 95% contains silicon (greens)



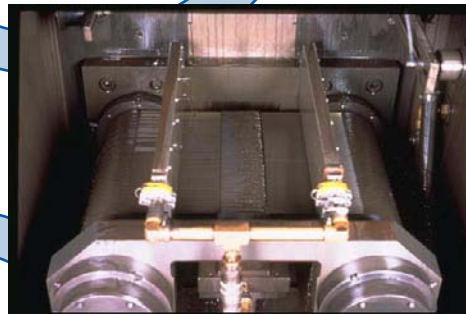
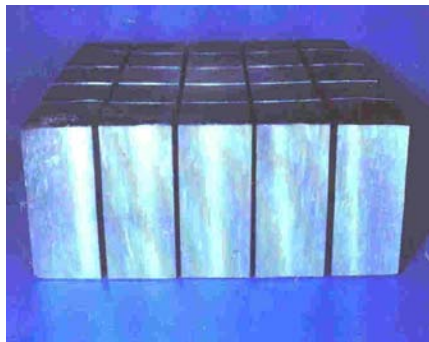
Crystalline Silicon = Wafers

Single Crystal Si



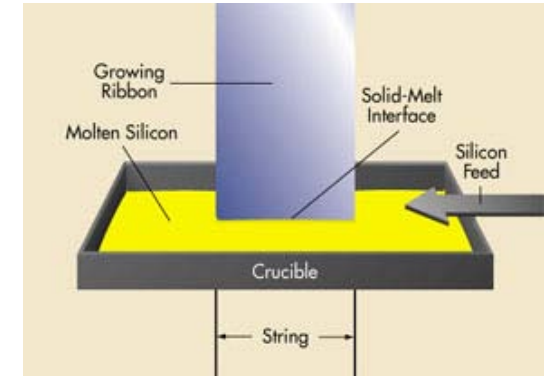
Wafering

Multicrystalline Si

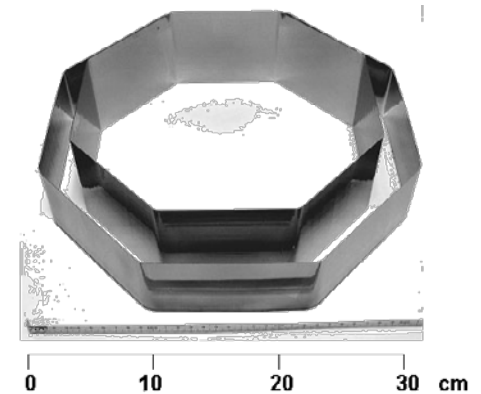


Ribbons ≠ Wafering

String Ribbon Si

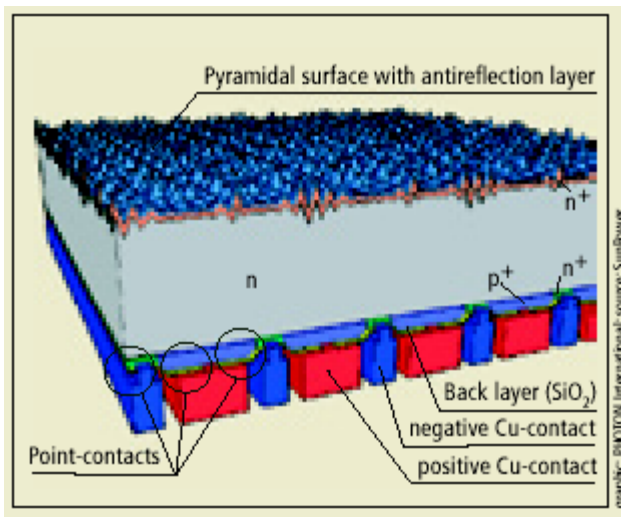


Edge-Defined Film-Fed Growth (EFG) Si



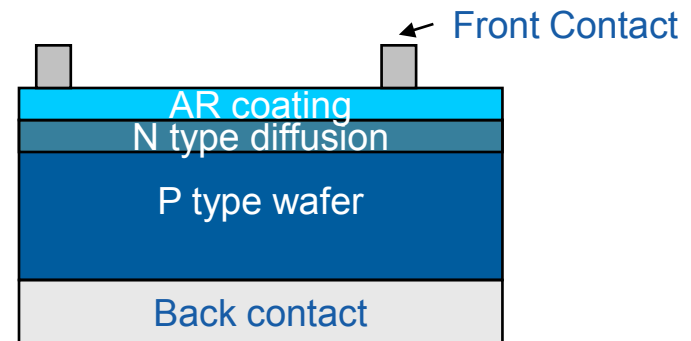
c-Si – Device Structure

Best Commercial Sample Structure

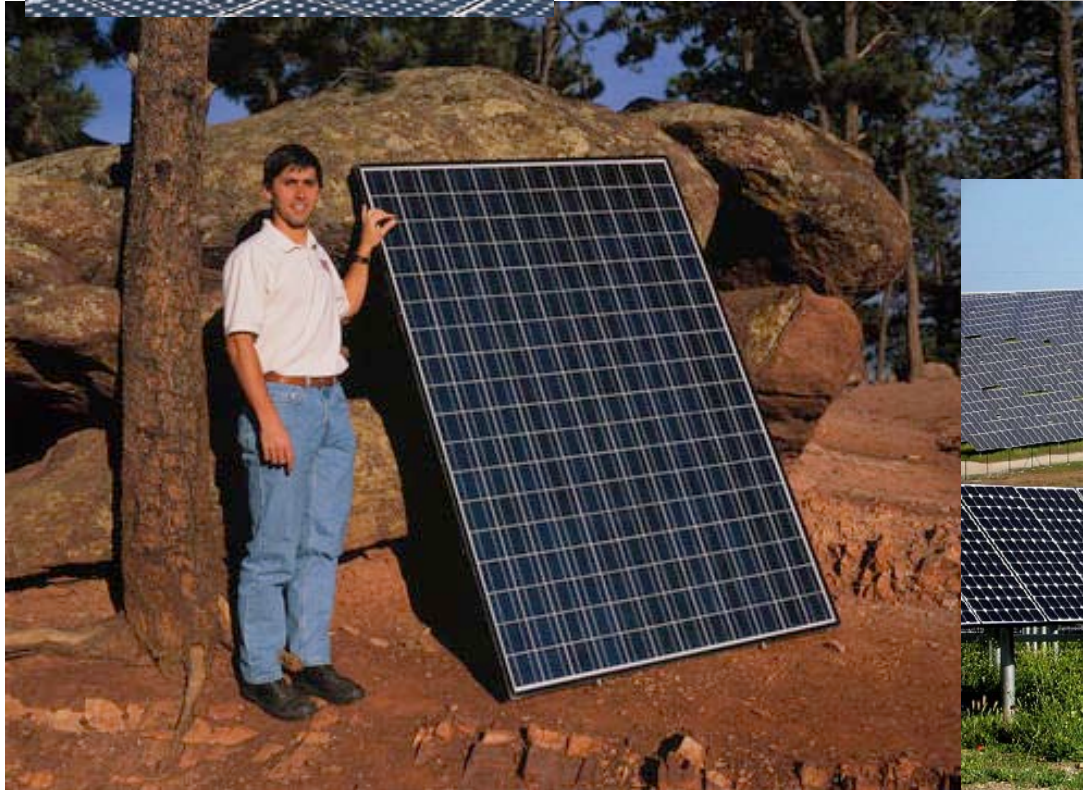


Point-contact cell
SunPower – 21.5%

Common Industrial Cell Structure



C-Si Modules



Crystalline Silicon (c-Si)

Pros

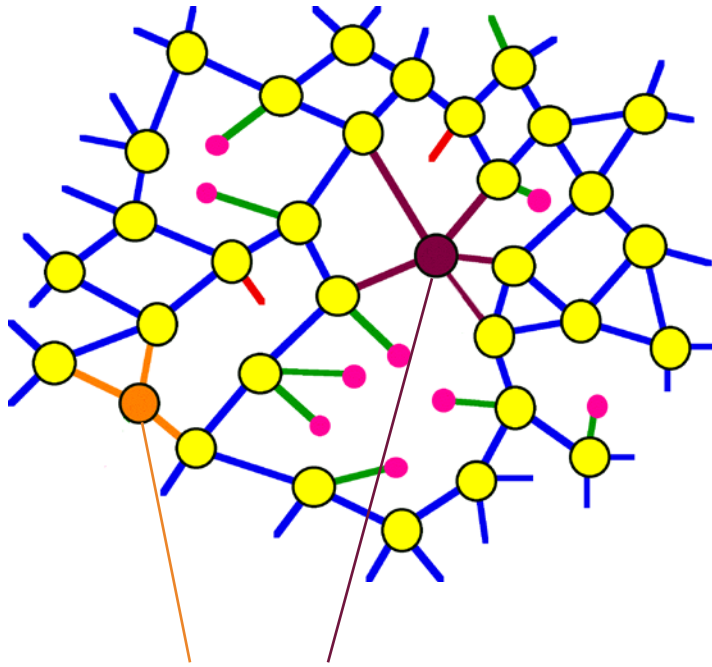
- Well understood material system because of IC industry
- Equipment to production is readily available from multiple vendors.
- Lower barriers to entry for new companies
- Elemental abundance

Cons

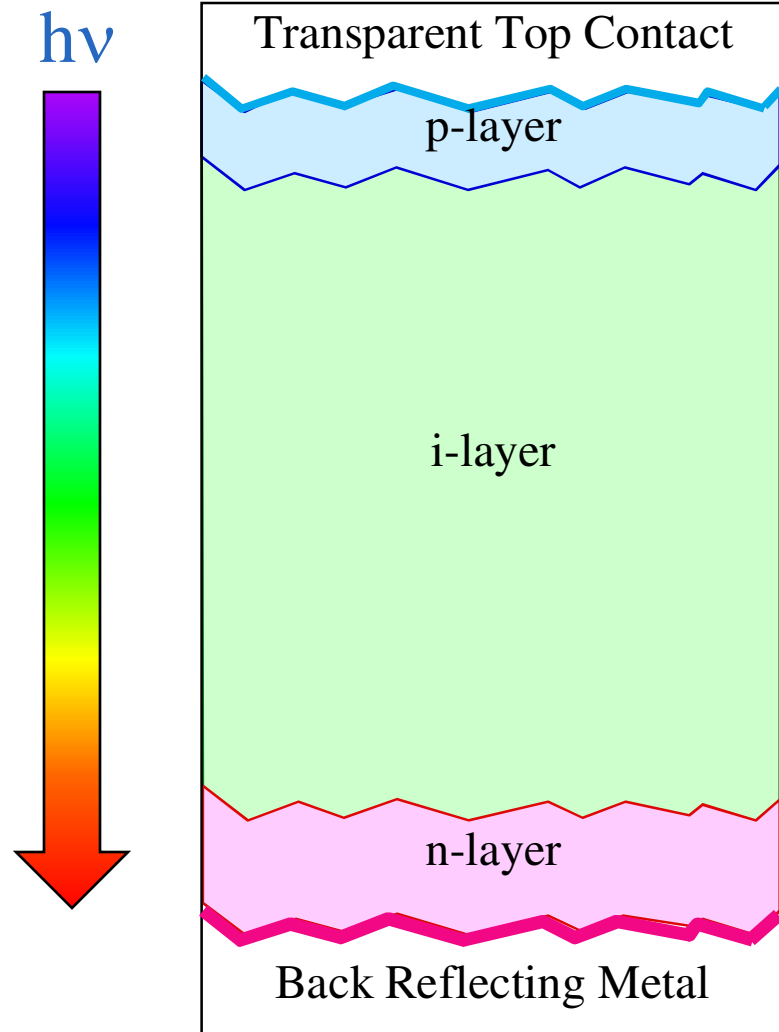
- Si wafers are energy intensive to manufacture
- Feed stock processing growth rate constrains growth
- Actually a family of several device structures, substrates, and production technologies
- Indirect band gap
- Not monolithically processed
- Wafer technology (too thick ~ 200 microns)
- Not many web-coating applications

Amorphous Silicon: Very Thin

a-Si:H

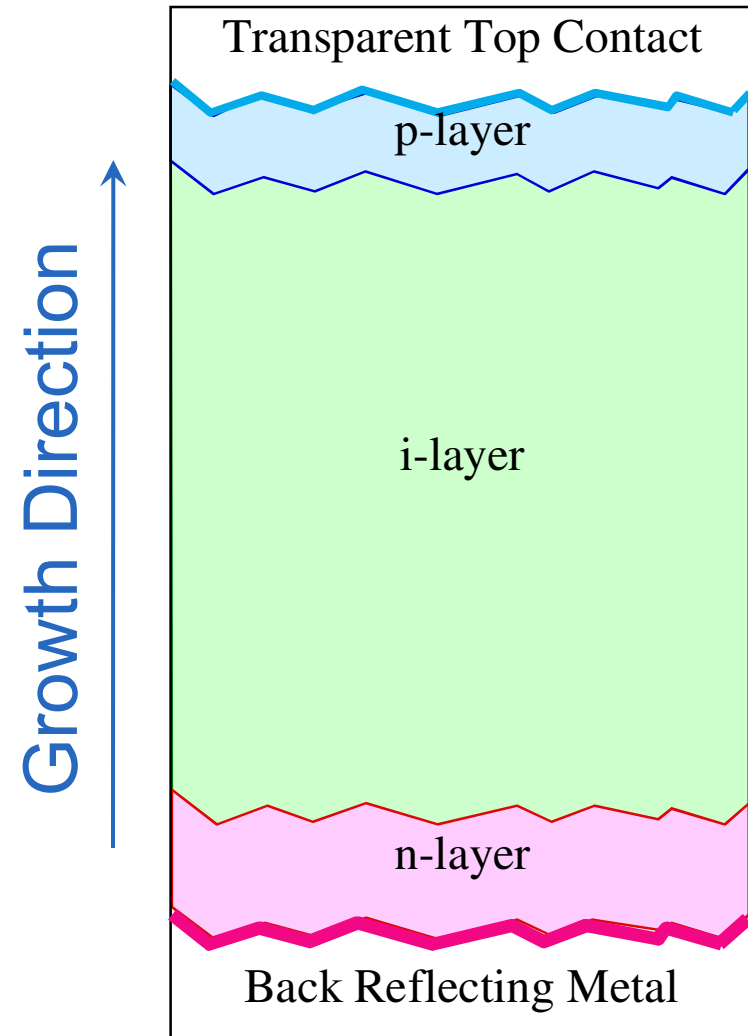


B or P dopants
can be fully satisfied
 \therefore need %-levels



Typical Growth Techniques

- Encapsulation
- Laser Patterning
- Top Contacts
 - Metal Grids... fingers by PVD or wire
 - TCO's... ZnO, ITO by PVD
- Semiconductor Layers
 - CVD techniques
 - PVD in research
- Bottom Contacts
 - Metals... Ag, Al, by PVD
 - Texturing... ZnO by PVD



a-Si:H Modules



Amorphous Silicon (a-Si:H)

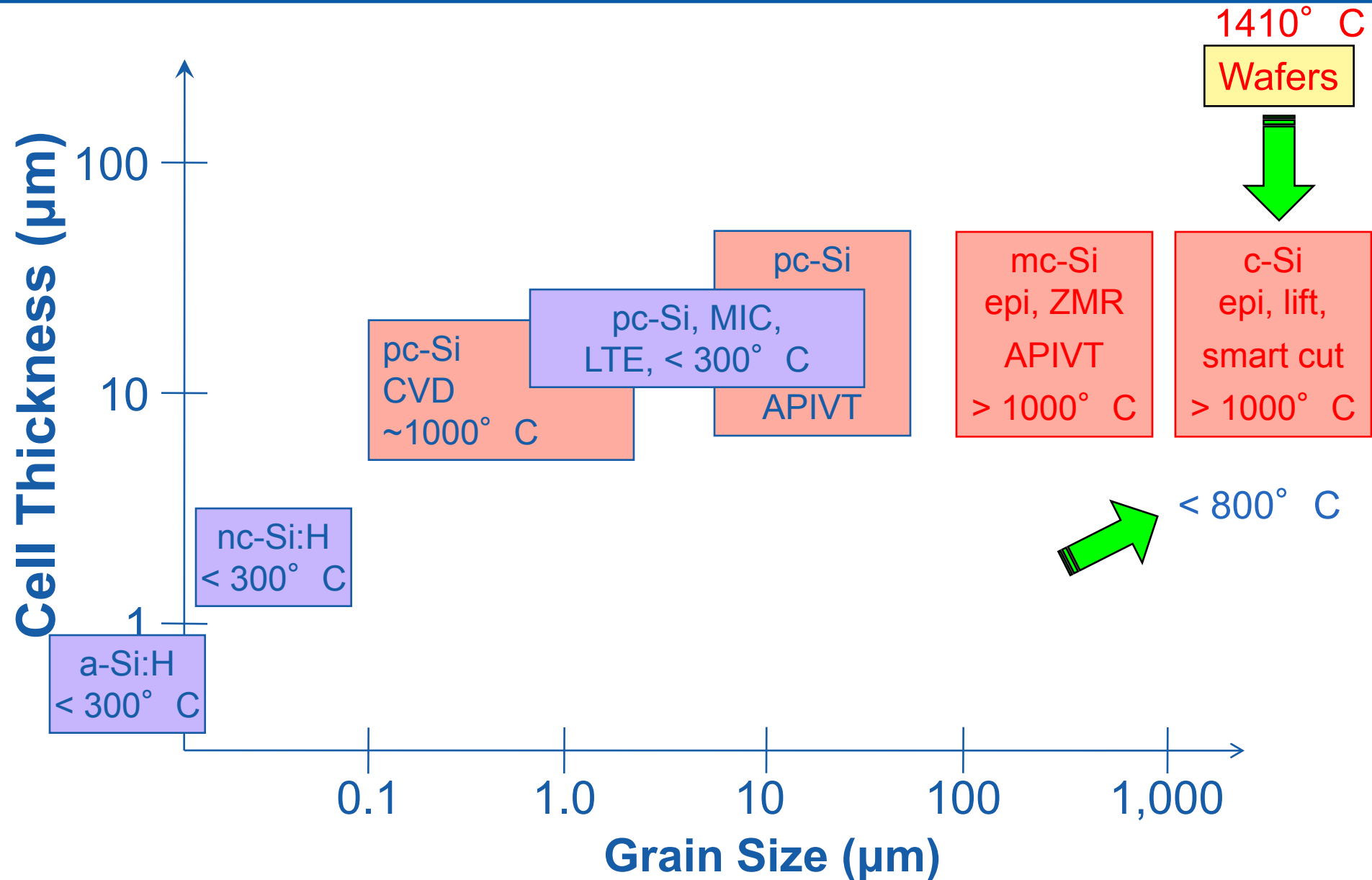
Pros

- Well understood material system
 - lots of science
- Leverage off TFT industry
- At least three companies selling “turn key manufacturing” facilities
- Elemental abundance
- Scalable manufacturing techniques
- Low temperature processes
- Very thin absorbers
- Many web-coating applications

Cons

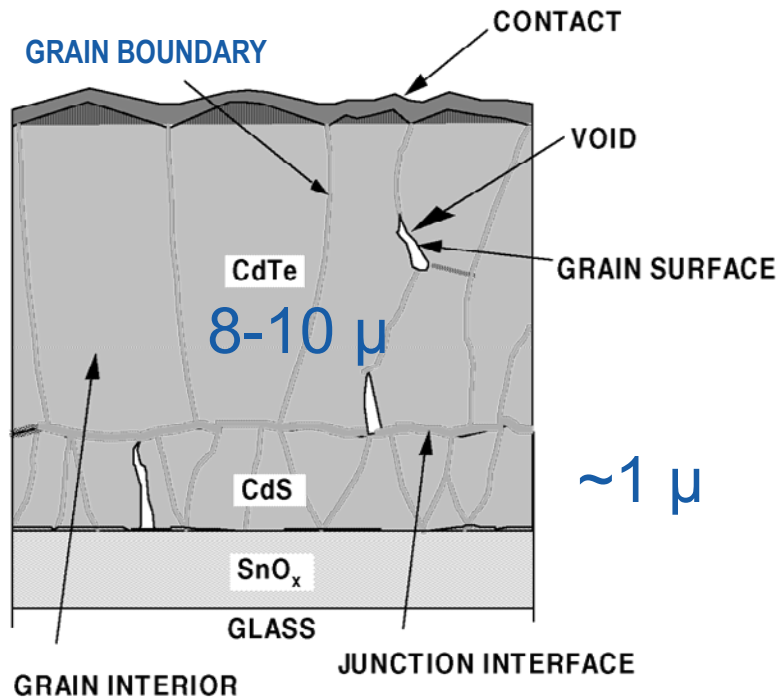
- Doesn't work well in red end of solar spectrum
- Low hole-mobility
- Light induced metastability
- Lowest efficiency of readily available technologies
- Many size “standards”
- Many substrate “standards”

Future of Film-Silicon PV

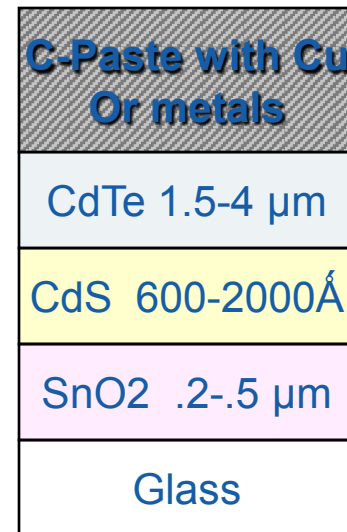


CdTe – Device Structure

Best Laboratory sample structure



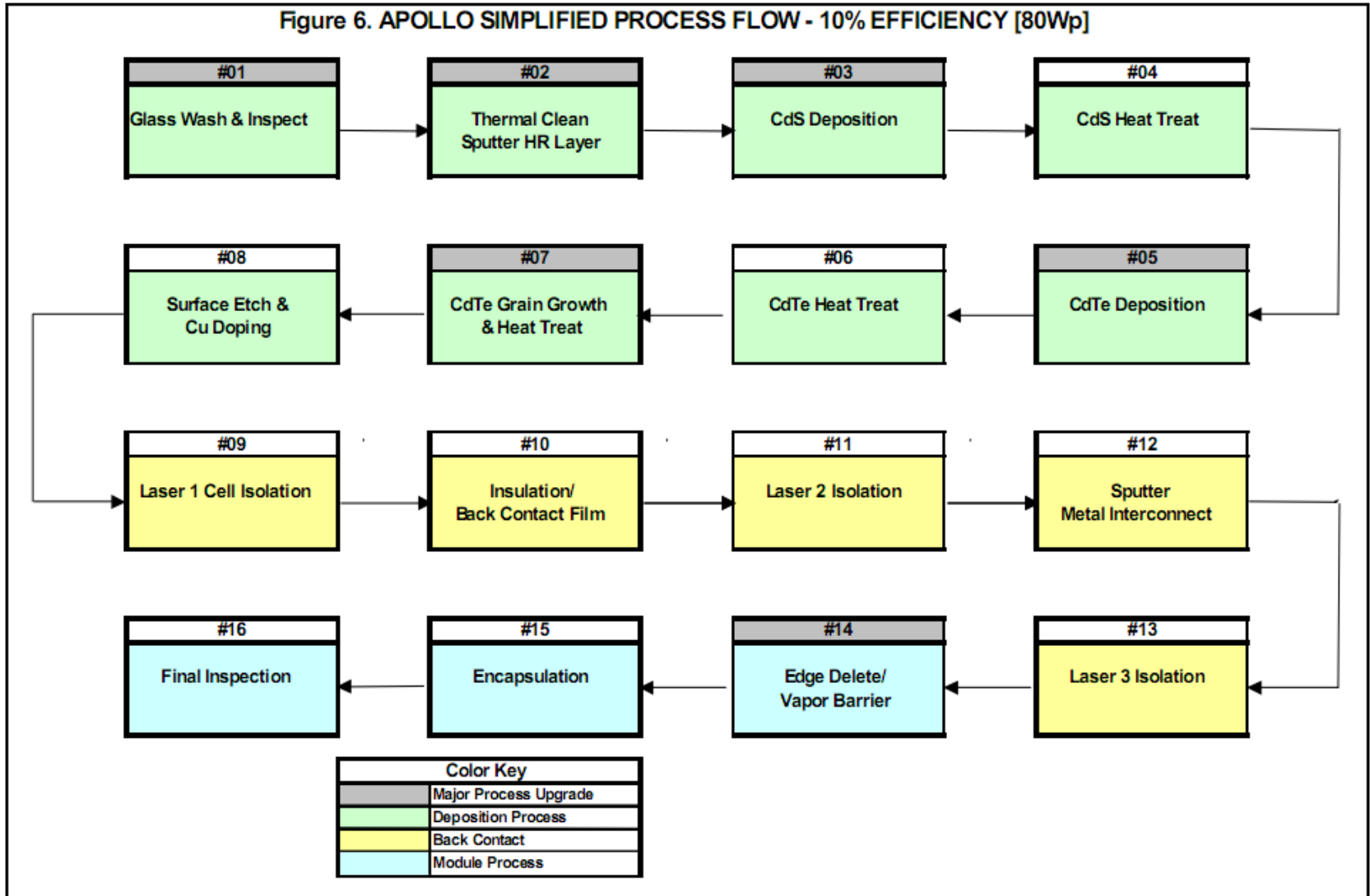
Common Industrial module structure



↑
Process
Direction

“Typical” CdTe Process

Figure 6. APOLLO SIMPLIFIED PROCESS FLOW - 10% EFFICIENCY [80Wp]



CdTe Modules



CdTe – Thin film

Pros

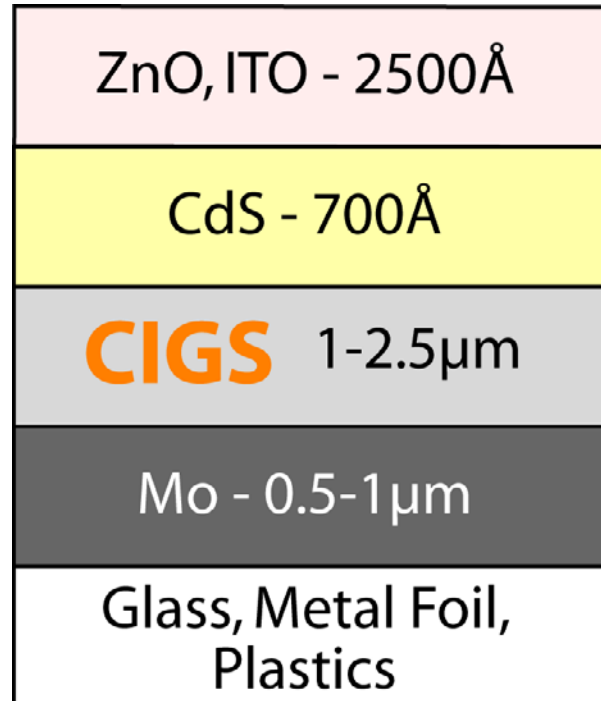
- Low Manufacturing Cost
- Highest deposition rate of absorber materials = good Manufacturability
- High efficiency laboratory cells = great promise
- Best Laboratory: > 16%
- Champion Modules at 12.5%
- Monolithic Module construction
- Nice Aesthetics
- 2 component manufacturing that is very impurity tolerant

Cons

- Not as well understood as Si materials
- No Industry standard size or fabrication techniques
- No one sells equipment to build these modules.
- Commercial Modules: 8-10.5
- Cd toxicity issues are know, and CdTe toxicity issues are being debated.
- Not currently many web-coating applications

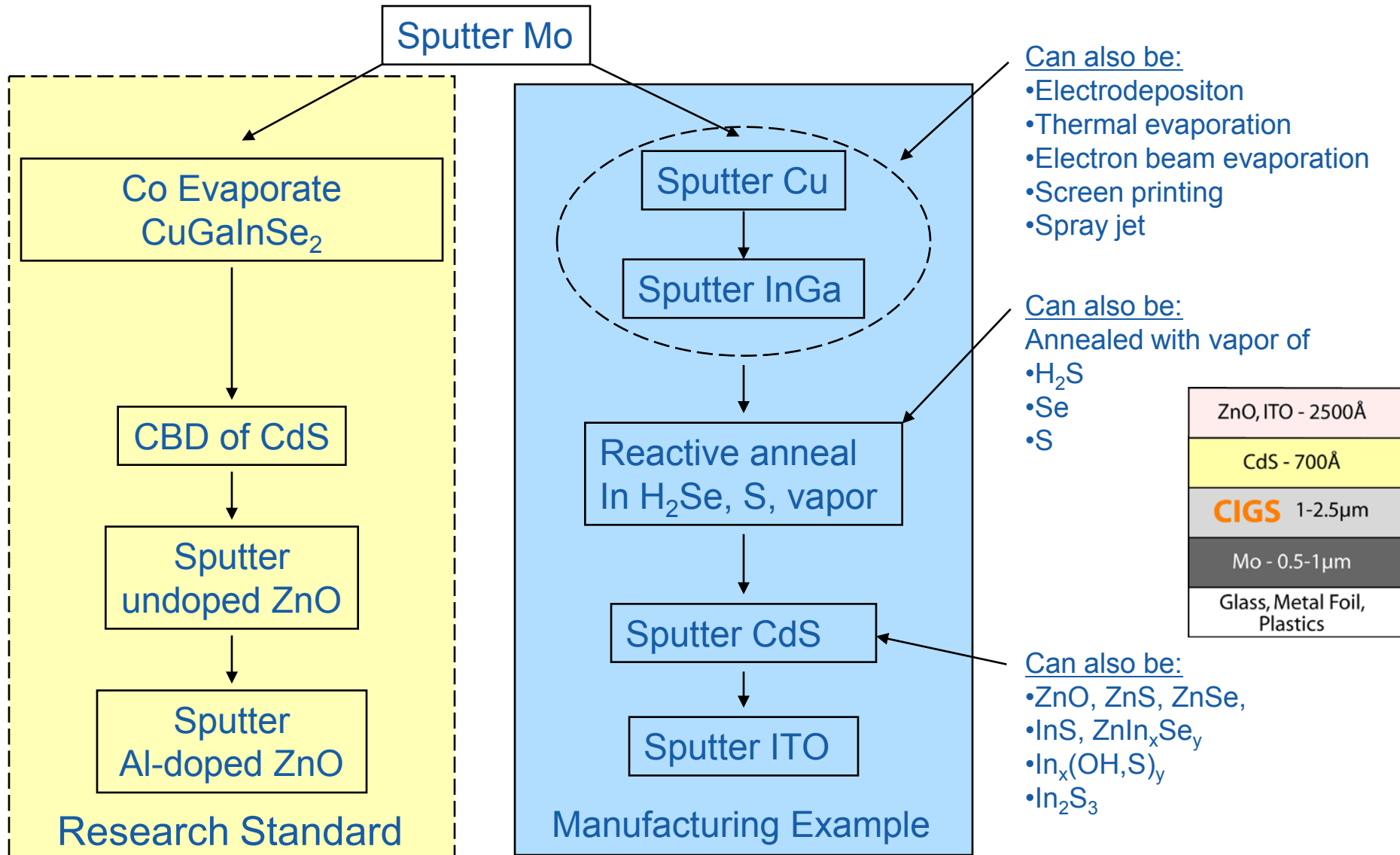
CIGS – Device Structure

↑
**Process
Direction**



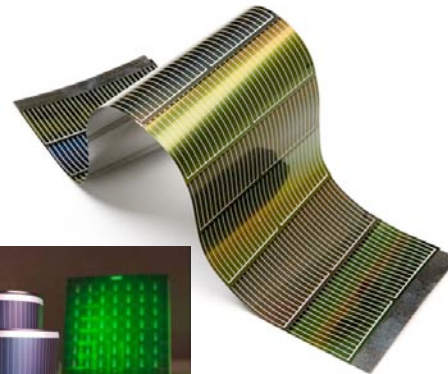
- Zn - Zinc
- O - Oxygen
- Sn - Tin
- Cd – Cadmium
- S – Sulphur
- Cu - Copper
- In - Indium
- Ga - Gallium
- Se – Selenium
- Mo - Molybdenum

“Typical” CIGS Process



Ref: Handbook of Photovoltaic Science and Engineering, Luque and Hegedus, chapter 13, Shafaman and Stolt, p 583.

CIGS Modules



CIGS – Thin film

Pros

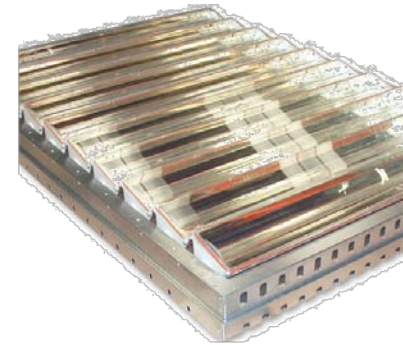
- Possible low manufacturing cost
- Possible high deposition rate of absorber materials
- Highest efficiency laboratory cells = great promise
- Best Laboratory: > 19.9%
- Monolithic Module construction
- Very Nice Aesthetics
- Three “turn-key factory” companies
- Many web-coating applications

Cons

- Requires large area stoichiometry of 4 elements
- High efficiency processes require strict uniformity
- Not as well understood as Si materials
- No Industry standard for size or fabrication techniques
- Best Commercial Modules: 13.4%
- Increasing deposition rates lowers efficiency

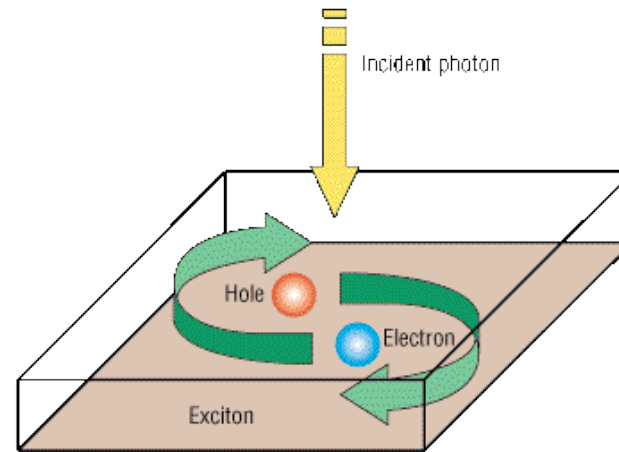
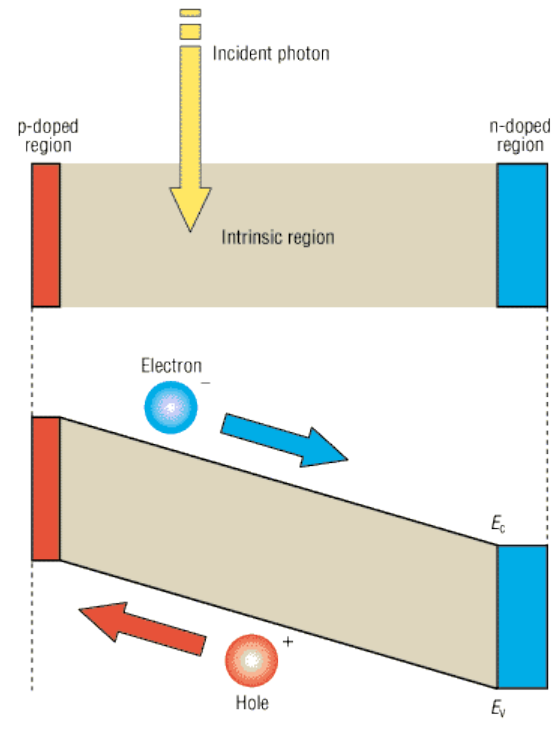
Concentrator Photovoltaics (CPV)

- Flat plate collectors
 - cover large areas with low cost cells
 - don't require external optics
- Concentrator
 - high efficiency cells
 - cover large areas with low cost external optics
- Mid to high-concentration PV systems
 - high-efficiency III-V or Si cells
 - trackers
 - reflective optics or
 - refractive optics
- CPV is inherently system-oriented
- CPV requires direct sun (SW USA)



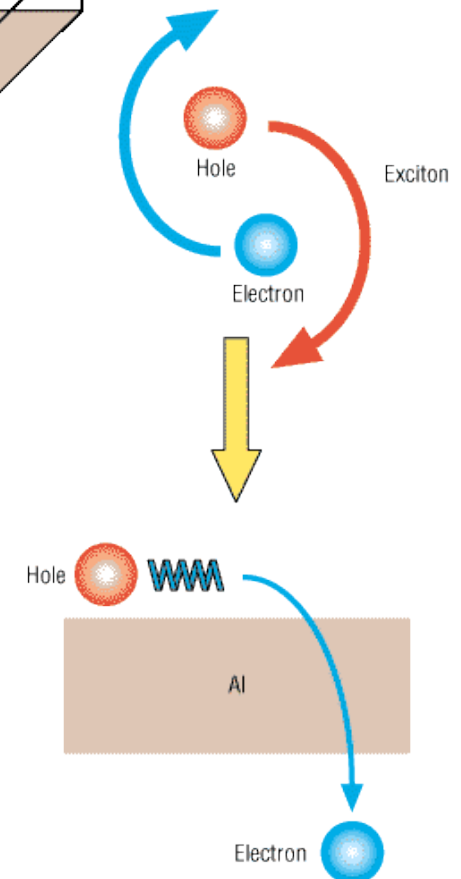
Exciton-Based Materials

Traditional Semiconductor



Conducting Polymer

Charge Separation at Interface



Organic Solar Cells

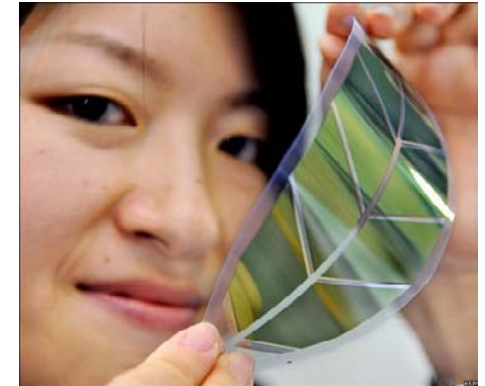
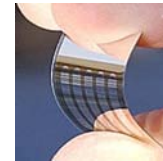
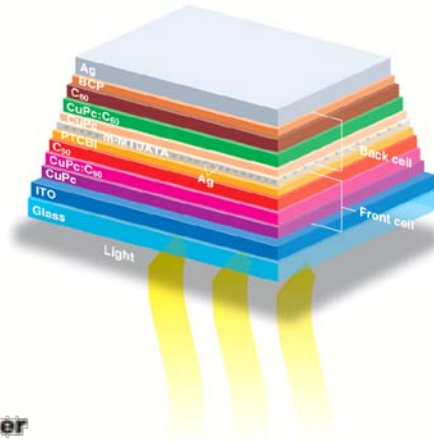
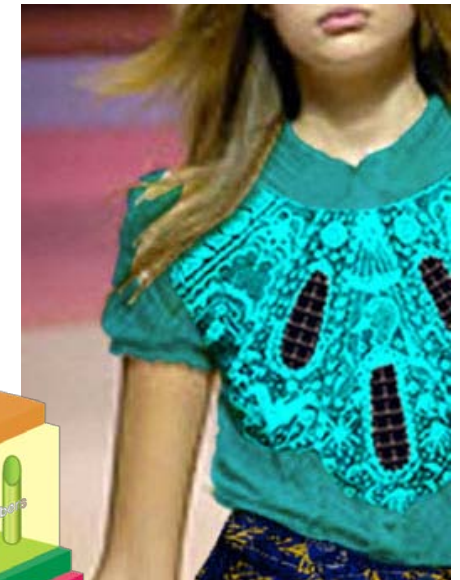
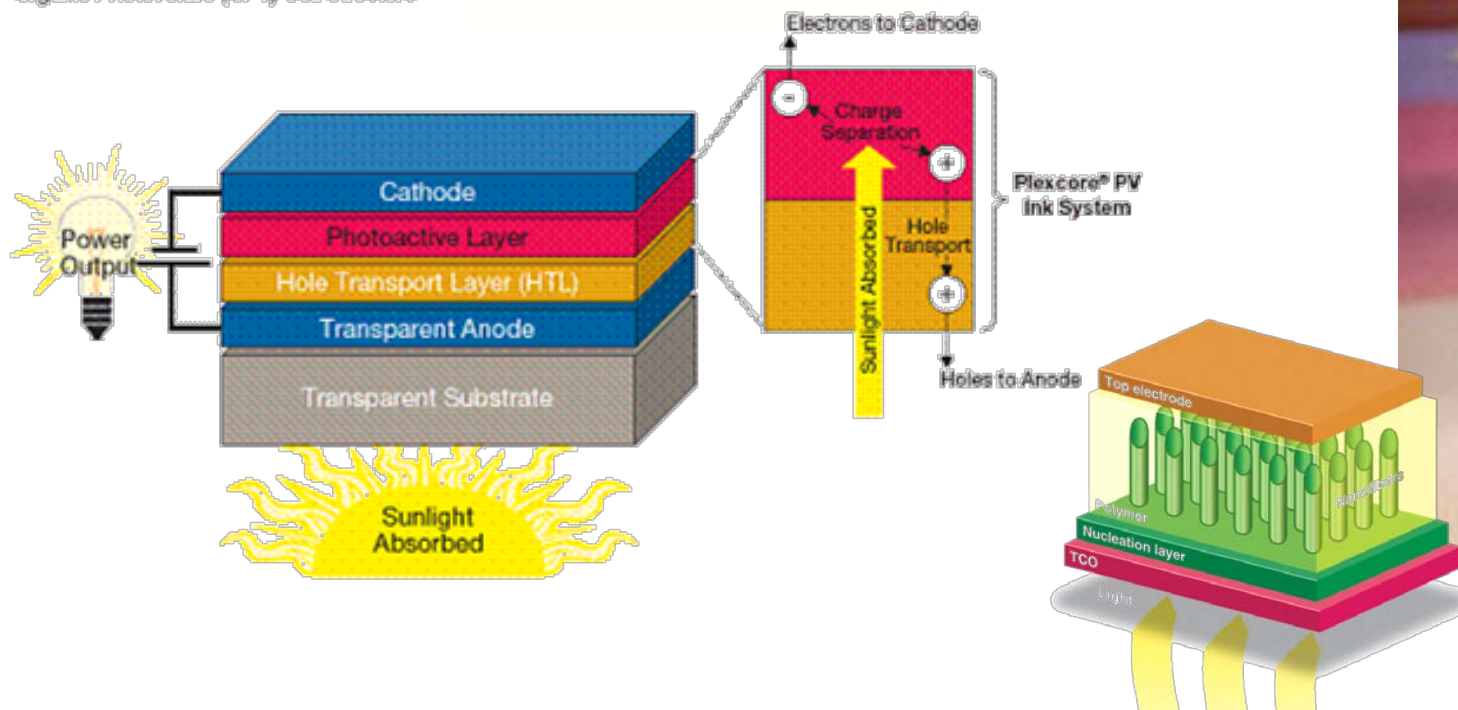
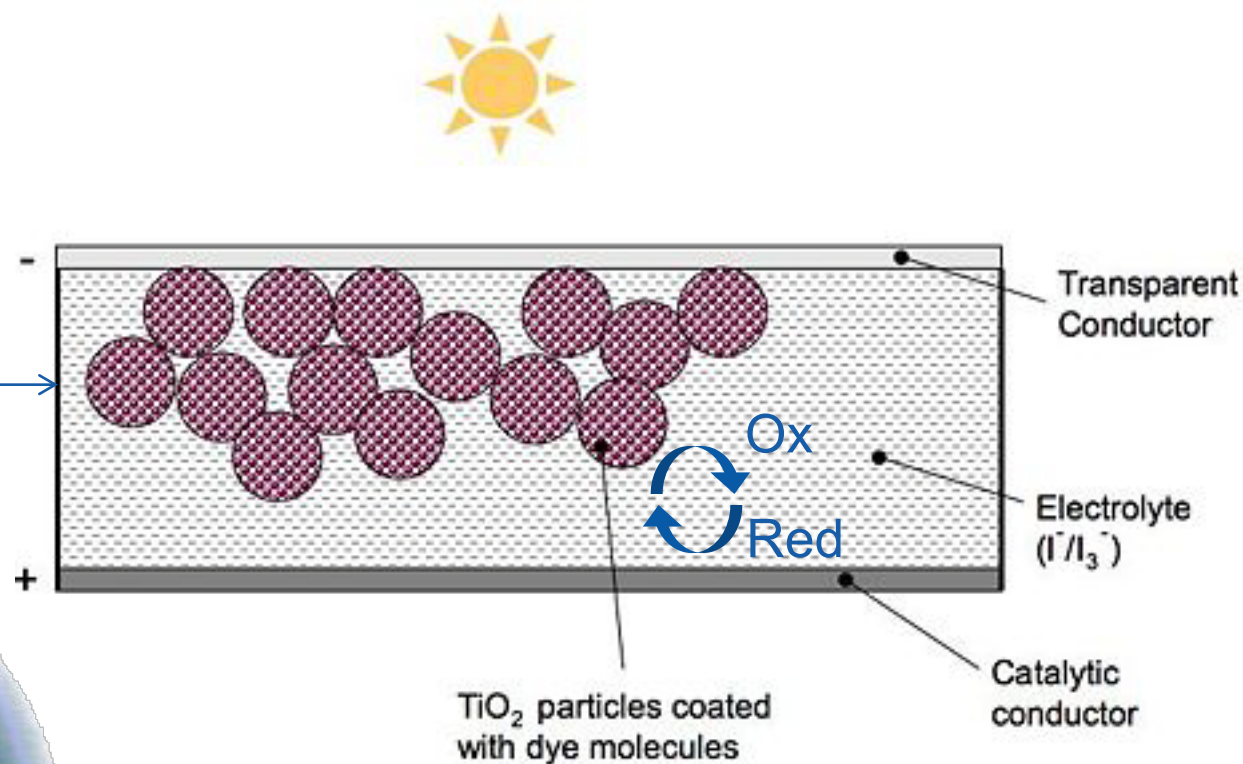


FIGURE 1
Plexcore® PV for Printed Solar Power
Organic Photovoltaic (OPV) Cell Structure

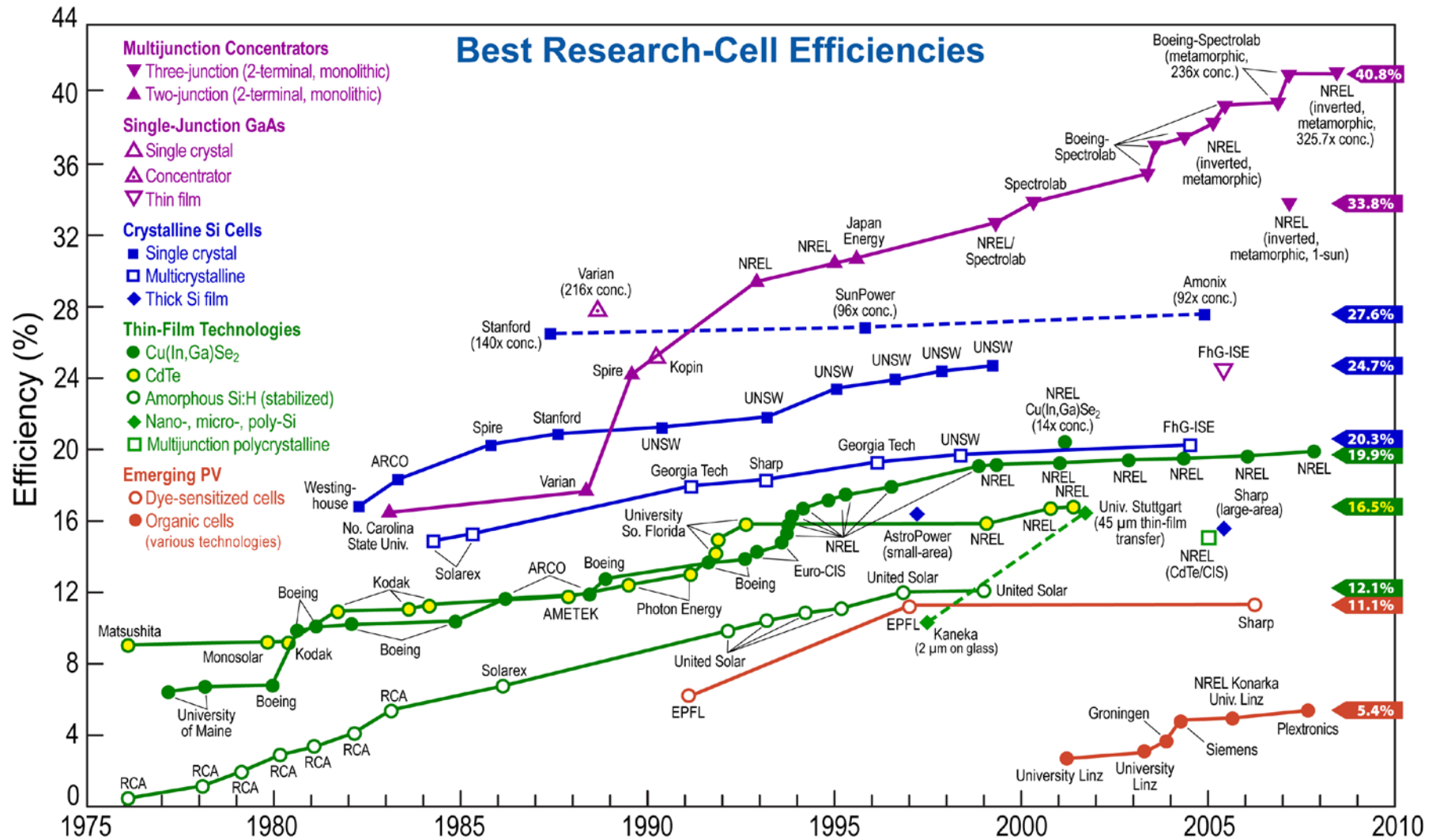


Grätzel (Dye-Sensitized) Cells

High surface area
for ruthenium-
polypyridine dye

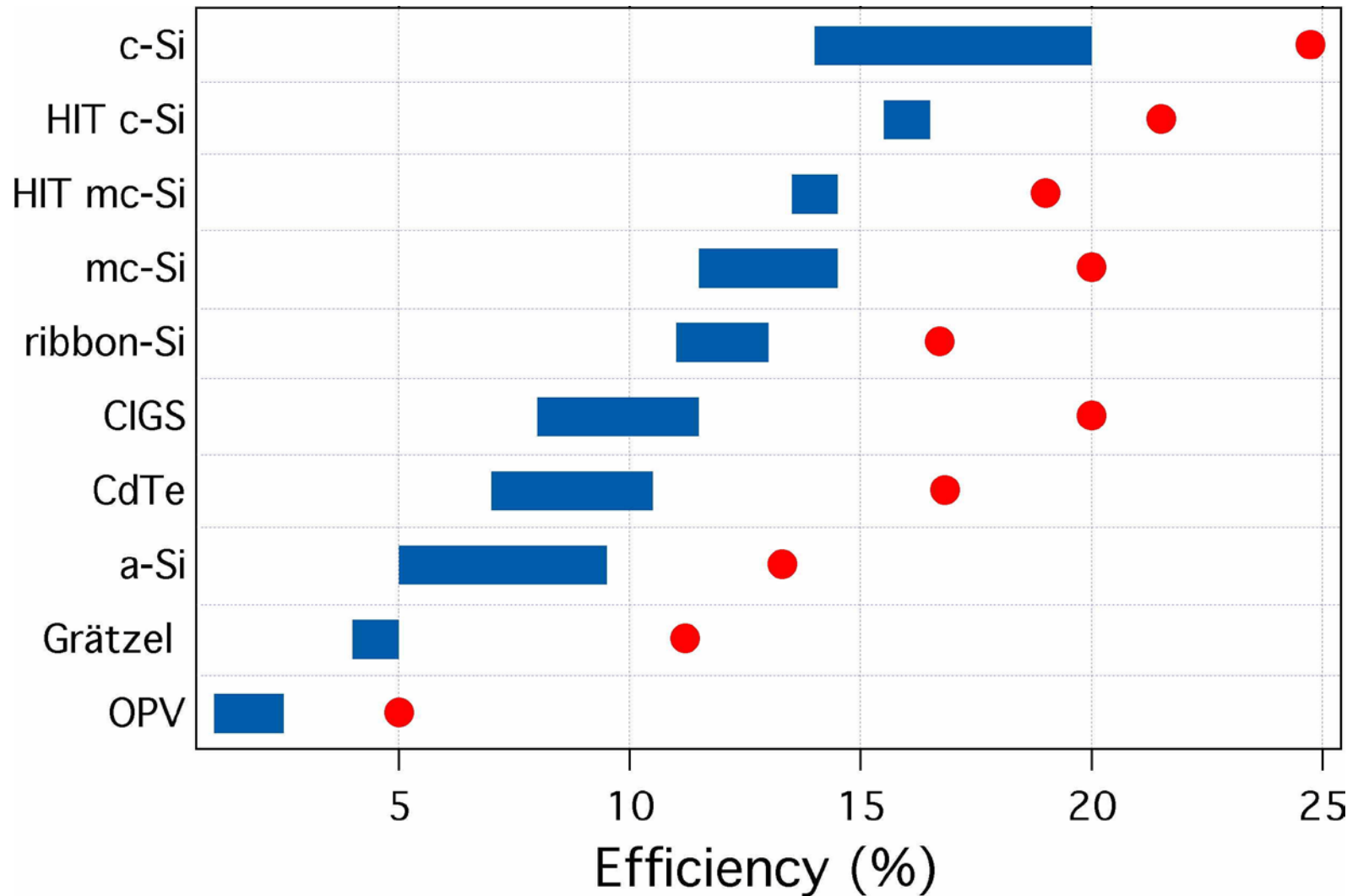


All PV Technologies are Improving



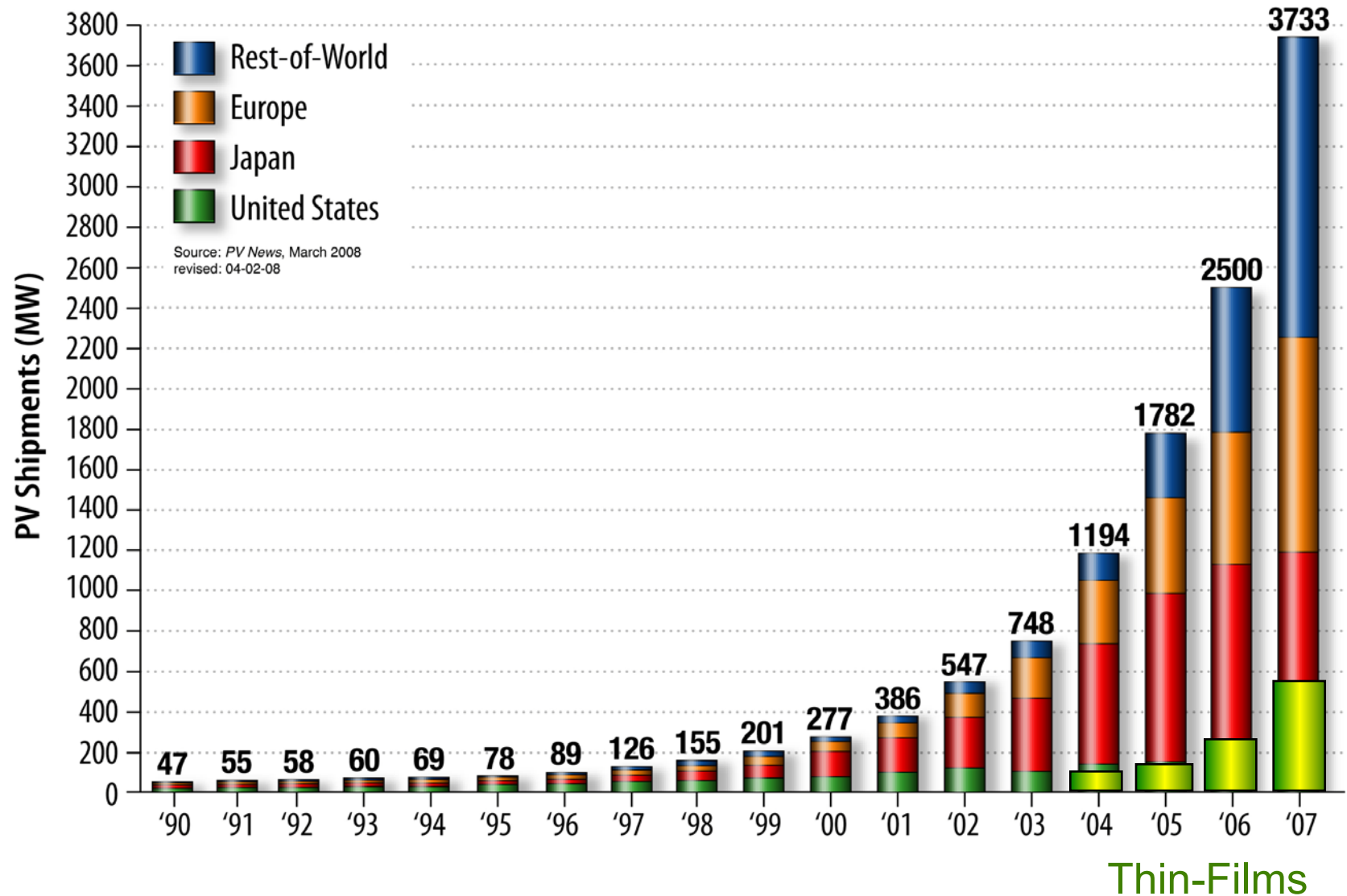
Rev. 06-08

Flat Panel PV Modules & Cells

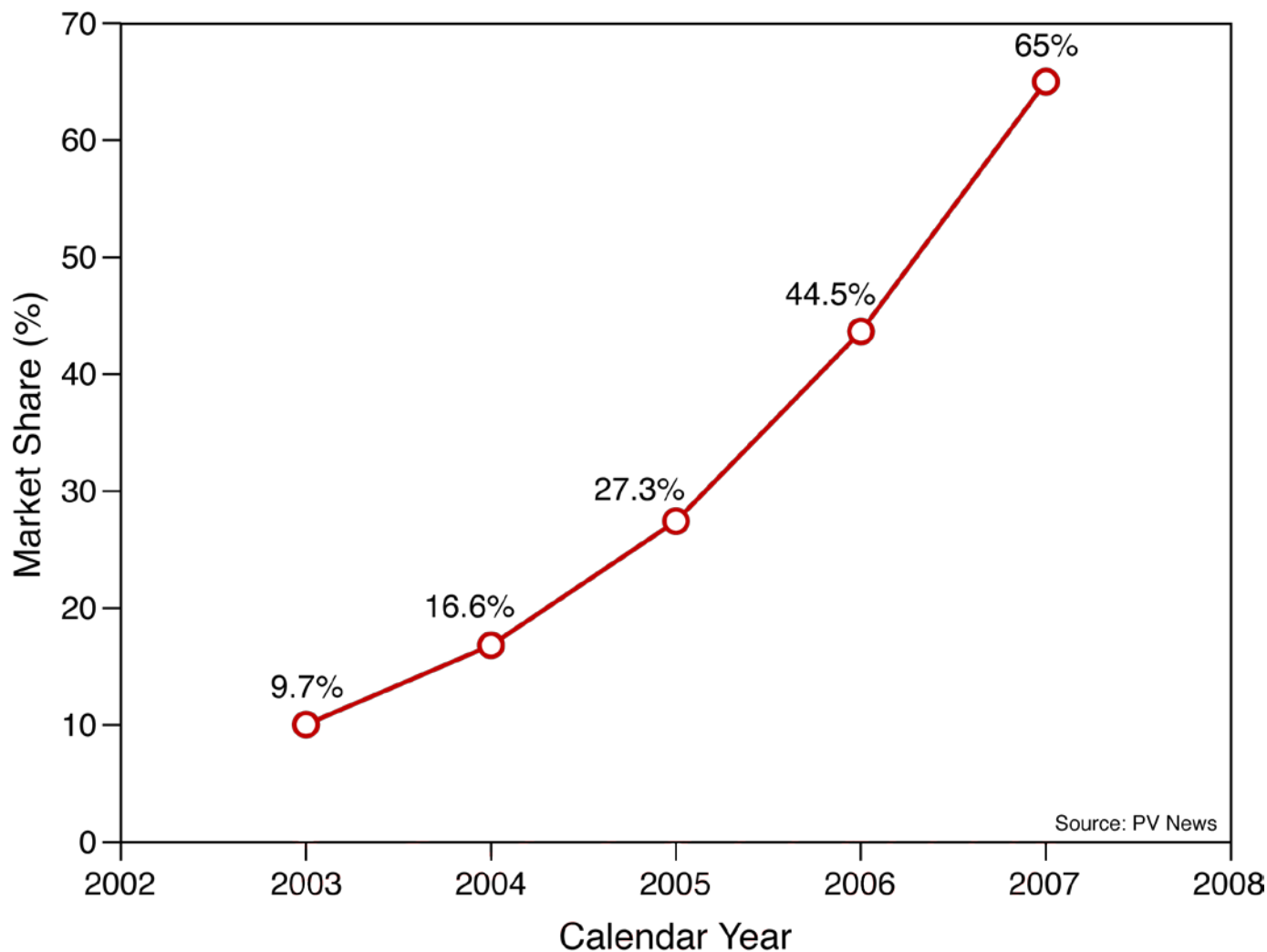


From Citigroup Global Markets, equity research,
Applied Materials, Inc, (AMT), 19 Feb. 2008


Worldwide PV Module Production



Thin-Film Market Share in the USA



Conclusions

1. The sun is the BIG energy player
 2. PV can (should) be a big part of the Energy Portfolio
 3. Some PV types have web-coating applications
 - a) crystalline silicon (c-Si) - LOW
 - b) amorphous silicon (a-Si:H) - **VERY HIGH**
 - c) cadmium telluride (CdTe) - POTENTIAL
 - d) copper indium gallium selenide (CIGS) - **HIGH**
 - e) others (CPV, OPV, DSSC, etc.) – **VERY HIGH**
 4. PV industry is “a mile wide and an inch deep”
 5. PV production growing a 35%++ annually
- 
- but still very small